MEASUREMENTS OF MAGNETIC FIELDS ON COOL STARS

Steven H. Saar
Joint Institute for Laboratory Astrophysics
University of Colorado and NBS, Boulder, CO 80309, USA

ABSTRACT. I discuss the some of techniques used (and problems involved) in measuring stellar magnetic fields on cool stars, and detail how these measurements are broadening our understanding of stellar magnetic activity.

1 INTRODUCTION AND A BRIEF HISTORY

Magnetic fields lie at the heart of the so-called "solar-stellar connection", playing a crucial role in the structure, energy balance, and evolution of the atmospheres of cool stars. The detailed physics of the these interactions, however, remains elusive, in part due to the lack of information about stellar magnetic parameters. The need for direct measurements of magnetic field strengths and the fraction of the stellar surface that cover is clear.

Unfortunately, magnetic fields on cool stars are quite difficult to measure. The detection of magnetic fields on cool stars is hampered by the locally bipolar topology of the fields themselves, which effectively cancels the circular polarization signal from the unresolved stellar disks (e.g., Borra, Edwards, and Mayor 1984). Linear polarization, which does not cancel in integrated starlight, has been recorded in broadband measurements for a few stars (Huovelin *et al.* 1985), but is difficult to interpret (Landi Degl'Innocenti 1982). Consequently, efforts to detect the magnetic fields of solar-like stars through polarization in spectral lines have been largely unsuccessful.

A breakthrough came when Robinson (1980) devised a method of measuring stellar magnetic fields in *unpolarized* light by studying the subtle Zeeman broadening of magnetically sensitive line profiles relative to insensitive reference lines. Such an analysis can provide an estimate of the fraction of the stellar surface that is covered by magnetic fields in addition to the field strength itself. Qualitatively, a line profile is modeled as $F = fF_{mag} + (1\text{-}f)F_{quiet}$, where F_{mag} and F_{quiet} are the line flux profiles in the magnetic (with a field strength equal to B) and quiet (B = 0) regions, and f is the magnetic area filling factor. For simplicity, the models used so far assume that the the thermodynamic properties of the magnetic and quiet regions are identical. The resulting magnetic parameters f and B therefore refer to elements of the stellar surface analogous to "bright" magnetic regions on the Sun such as network and plage.

G. Cayrel de Strobel and M. Spite (eds.), The Impact of Very High S/N Spectroscopy on Stellar Physics, 295–300.

https://doi.org/10.1017/S0074180900035178 Published online by Cambridge University Press

The effects of a magnetic field on an unpolarized line profile are subtle, however, and difficult to measure accurately. Differences between magnetically sensitive (high Lande g) and insensitive (low g) lines are generally only a few percent of the continuum, requiring high signal-to-noise (S/N) spectra. Typically $S/N \geq 50$ is necessary, although the exact figure depends on the values of f and B as well as other observational and stellar parameters (Marcy 1982; Saar 1987). The magnitude of the Zeeman broadening itself is quite small, since the splitting of the magnetic components is only $\Delta\lambda_B = 4.2 \times 10^{-3}(g/2.5)(\lambda/600\ \mathrm{nm})^2(B/1000\ \mathrm{G})$ nm . Thus, high spectral resolution is also needed. The minimum spectral resolution ($\lambda/\Delta\lambda$) required is approximately $2\Delta\lambda_B$, which corresponds to at least 75,000 at 600 nm and 40,000 at 2 μm. Ideally, S/N = 100 - 200 and a resolution of 100,000 should be obtained. Stellar rotation imposes further limits magnetic measurements, since rotational line broadening can overwhelm the magnetic broadening signal for $v \sin i > 10$ km s^{-1}.

Unrecognized blends can also significantly effect the accuracy of the derived magnetic parameters (e.g., Gondoin, Giampapa, and Bookbinder 1985, Linsky 1985). Blends can cause broadening that mimics the Zeeman effect, leading to inaccurate or even spurious magnetic field detections. The ubiquitous molecular opacity sources in K and M dwarf atmospheres, for example, render magnetic field measurements at optical wavelengths extremely difficult for these stars.

In spite of these difficulties, numerous measurements of magnetic fields on cool stars have been made over the past several years. Following the initial detection of ξ Boo A by Robinson, Worden, and Harvey (1980), subsequent measurements of the star by Marcy (1981) found no evidence for Zeeman broadening, the first indication of magnetic variability on an active dwarf. At about the same time, attempts to study correlations between simultaneous measurements of magnetic, chromospheric, and coronal fluxes were made (Basri, Walter, and Marcy 1981). Giampapa, Golub, and Worden (1983) discovered magnetic fields on an active giant (λ And) in the first use of infrared spectra for magnetic field determinations. A major accomplishment was Marcy's (1983, 1984) publication of the results of the first extensive survey of magnetic field parameters for 29 late-type dwarfs. Gray (1984) serendipitously discovered Zeeman broadening in several more dwarfs during the course of studies of stellar rotation. Marcy and Bruning (1984) searched for magnetic broadening in 8 late-type giants and subgiants, but found none.

Some of the results of these early studies were rather suprising, however. Some stars with only moderate levels of activity showed filling factors of nearly 90 % (e.g., ϵ Eri). Other, quite inactive stars showed similar amounts of magnetic flux (e.g., 61 Cygni A, τ Ceti). Enormous swings in the surface magnetic field and filling factor appeared to take place on timescales of a day. The total flux ($\propto$ fB), however, remained roughly constant in time. Indeed, Gray (1985), in an examination of all magnetic measurements on cool stars published to that date, noted that the product fB was a constant independant of spectral type and rotational velocity. Thus, the early magnetic measurements seemed to indicate that all stars produced the same amount of magnetic flux, contrary to observations of stellar "activity" indicators and to the expectations of dynamo theories.

2 NEW METHODS, RESULTS, AND FUTURE PROSPECTS

It now appears that the rather curious results of the initial magnetic field surveys were the result of simplifying assumptions used in the Zeeman broadening analyses. In particular, the early methods assumed that all lines were simple Zeeman triplets on the linear part of the curve-of-growth, and could therefore be constructed by essentially adding together three appropriately shifted low g line profiles. As one might anticipate, this approximation is inappropriate for the moderately strong lines employed in the Zeeman broadening studies, and its use leads to systematic errors in the derived magnetic parameters (Saar 1987; Hartmann 1987). Weak line blends, which will affect the cores and wings of stronger lines in different ways, also introduce systematic errors in the derived f and B values.

To help remedy this situation, I have developed some new methods for deriving magnetic parameters from spectra of cool stars (Saar, Linsky, and Beckers 1986, Saar 1987) which include magnetic radiative transfer effects (Unno 1956), the full Zeeman patterns, and some compensation for line blends. The new technique models differences between line profiles, either comparing magnetically sensitive and insensitive lines from the same spectrum, or by comparing the same high g line in two stars of the same spectral type, one of which is known to be magnetically inactive. The latter, differential approach is used to eliminate the effects of blends to first order. The number of free parameters are minimized by determining the non-magnetic broadening parameters independently (from low g lines) and applying these results to the high g line models.

The new magnetic analysis methods have now been applied to a considerable body of data, and some preliminary trends can be discerned. 1) The product fB is not constant (Saar and Linsky 1986). Rather, fB and f increase with stellar angular velocity, consistent with simple ideas of the dynamo mechanism and the observed increase of chromospheric and coronal emission with rotation (Saar and Linsky 1986; Linsky and Saar 1987). There is some evidence for a saturation in f at high Ω (Saar, Linsky, and Giampapa 1987). 2) B increases with decreasing T_{eff} and increasing gravity and gas pressure down the main sequence. A possible cause of this is pressure equilibrium between B and the quiet photosphere ($B \propto P_{gas}^{0.5}$; Saar and Linsky 1986). 3) $f \propto t^{-0.6}$ while B is constant in time, in agreement with the observed dependence of Ω on t and suggesting that f is the dominant magnetic parameter governing stellar activity (Linsky and Saar 1987). 4) The mean strength of the surface field (= fB, the unsigned magnetic flux density) correlates with outer atmospheric emission such that the X-ray flux, $F_x \propto (fB)^{0.9}$ and the residual Ca II flux (Schrijver 1983), $\Delta F_{CaII} \propto (fB)^{0.6}$, consistent with relations derived for the Sun, and with flux-flux relations derived for stars (Saar and Schrijver 1987). Rotational modulation of chromospheric and transition-region line fluxes with magnetic flux for the active dwarf ξ Boo A support this picture, and when combined with measurements of broadband linear polarization, permit a rough determination of the spatial distribution of active areas on the star (Saar *et al.* 1987).

These results must be regarded as somewhat preliminary, however, since not all the line profiles have been modeled differentially to remove blends. Also, the data have been fit using convolutions for the velocity broadeneing, which is only an approximate method (Bruning 1984). Tests show that no single intensity profile can reproduce the shape of the disk-integrated flux profile (Fig. 1), implying the convolution approach could lead to systematic errors in the derived f and B values. We have therefore added full–disk integrations to the Zeeman line modeling codes to properly account for the rotational and turbulent line broadening, and are in the process of reanalyzing the data.

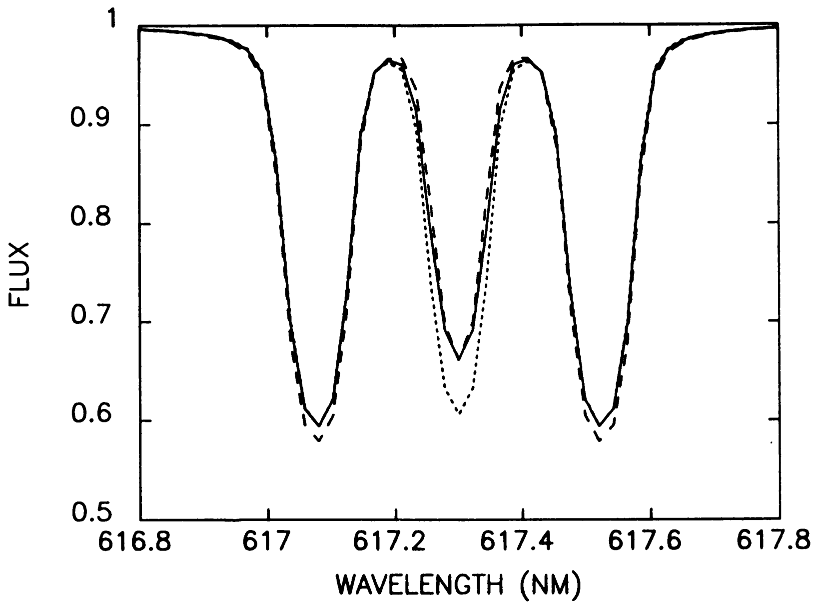

Figure 1. Comparison of computed disk-integrated magnetic flux profile (for a line–to–continuum opacity ratio of 10, g = 2.5, B = 5000 G, f = 1.0, v sin i = 0, and a limb darkening coefficient of 0.6; solid line) with intensity profiles computed at magnetic field to line–of–sight angles of $\theta = 31^o$ (dashed line) and $\theta = 48^o$ (dotted line). Note that the central π and the shifted σ components of the flux profile cannot be *simultaneously* matched by a single intensity profile.

Several further improvements to stellar Zeeman analysis are also on the horizon (and will be discussed in the following talks). Basri and Marcy (1986) and Marcy and Basri (1988) have developed codes which use the Unno formulation with a more realistic model atmosphere. Mathys (1987) and Mathys and Solanki (1988) are using a multiline correlation approach (after Stenflo and Lindegren 1977) which may yield information on the thermodynamic differences between the quiet and magnetic regions on the stars. Thus, the future promises to bring ever more accurate measurements of stellar magnetic parameters, and with it, better understanding of the stellar "activity" phenomenon.

This research is supported by NASA grant NGL-006-03-057 to the University of Colorado.

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DISCUSSION

MATHYS I would like to make the comment that radiative transfer effects are important not only in the case of saturated lines but also whenever the lines are not optically thin. As soon as you depart from the weak line limit, simple atomic parameters such as the effective Landé factor may no longer be sufficient to characterize the magnetic broadening.

SAAR Yes, I agree completely. We include both radiative transfer effects and the full Zeeman patterns for all the lines we model.

https://doi.org/10.1017/S0074180900035178 Published online by Cambridge University Press